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ARTICLE

Landscape Context Predicts Reed Canarygrass Invasion: Implications for Management

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Abstract Understanding the landscape distribution of invasive species has become an important tool to help land managers focus their efforts. We used land cover data to predict the proportion of wetlands in a watershed dominated by reed canarygrass (*Phalaris arundinacea* L.), one of the most dominant wetland invaders in North America over the past century. Our results indicated that the landscape configuration of a watershed was a better predictor than the landscape composition of a watershed, with the adjacency of wetlands to agriculture and open water identified as the best predictors of the proportion of wetlands in a watershed dominated by reed canarygrass. In contrast, proportion of agriculture and open water were identified as the next best predictors in our regression tree, but explained significantly less variability. These results suggest that the risk of invasion by reed canarygrass varies among watersheds, and further that the potential for restoration success may similarly vary across the landscape. We argue that it is essential to understand the landscape context of a wetland before attempting a restoration project because success may be mediated by factors outside the local site.

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Introduction

The number of invasive species, the amount of area at risk to invasion, and the negative impacts associated with invasion continue to grow (Babbitt 1998). As a result, there is a increasing need for focused, effective management (Mooney and Hobbs 2000). Because the area at risk of invasion usually exceeds the area capable of being managed, an important part of management is the ability to accurately map the current locations of invasion, predict the risk of invasion of non-invaded sites, and predict the potential for effective management at a given site (Hobbs and Humphries 1995; Higgins et al. 2000). Advances in the field include the mapping of invasion using remote sensing (Lass et al. 2005) and the development of spatially explicit models that predict the risk of invasion by a species (Higgins et al. 2000; Stohlgren et al. 2001; Westerberg and Wennergren 2003). The large scale at which invasion occurs generally makes it difficult to validate the predictive ability of invasion models, due to the large amount of time and resources necessary to inventory a large number of sites (Higgins et al. 2001). Thus, species that are capable of being measured using remote sensing imagery provide the best opportunity to evaluate invasion models at a large-scale.

MacDougall and Turkington (2005) offered a framework to classify invasive species as *drivers* or *passengers* of change. *Driver* species are capable of displacing native vegetation by direct competition irrespective of environmental change. Modeling these types of species is difficult because of the importance of random, long-distance dispersal (Higgins and Richardson 1999). *Passenger* species invade habitats in which environmental changes have shifted away from historic levels to create novel, unfilled niches that are invaded by exotic species. Often, these environmental changes can be predicted using landscape composition and configuration variables (O'Neill et al. 1997). Therefore, it is easier to model *passenger* invasive species than it is to model *driver* invasive species (Sebert-Cuvillier et al. 2008).

Reed canarygrass (*Phalaris arundinacea* L.*)* is a species that is capable of being accurately mapped using Landsat imagery because it senesces later than other species (Bernthal and Willis 2004). Reed canarygrass is a cool-season, long-lived perennial grass native to Eurasia and North America (Merigliano and Lesica 1998). The species has been intentionally planted throughout North America during the past century for animal forage and soil stabilization. It continues to be planted for agronomic purposes, and active breeding programs exist with the goal of improved forage quality and other agronomic traits. In recent years, reed canarygrass has become one of the most serious invaders of wetlands throughout North America, where it forms dense monocultures and chokes out native vegetation (Kercher et al. 2007). Reed canarygrass has several traits that make it potentially invasive in both riparian and upland habitats, including floating seeds, adventitious rooting, propagation by root fragments, tolerance of irregular hydrology, and drought tolerance (Lavergne and Molofsky 2004). Once established, it is capable of rapid vegetative and seedling expansion (Katterer and Andren 1999).

The *passenger* hypothesis of reed canarygrass suggests that the proliferation of reed canarygrass maybe a result of an expansion in the amount of suitable habitat for the species. Reed canarygrass is capable of out-competing other wetland vegetation when there are high nutrient levels (Maurer and Zedler 2002), irregular hydrology (Maurer et al. 2003), and high levels of sediment (Werner and Zedler 2002). The intensification of agriculture, alteration of hydrology, and expansion of urbanization throughout North America since World War II has led to the eutrophication and sedimentation of many wetlands (Pimentel et al. 1995). This expansion in area of the preferred habitat of reed canarygrass has likely led to an increase in the establishment and expansion of reed canarygrass populations and may allow spatially explicit models of reed canarygrass invasion to be developed from simple land cover maps (Green and Galatowitsch 2001; Lindig-Cisneros and Zedler 2002; Kercher and Zedler 2004).

The objective of this study was to develop spatially explicit predictive models of the proportion of wetlands dominated by reed canarygrass using the composition and configuration of land cover at the watershed scale. In particular, we used regression tree models to identify the land cover variables that best predicted invasion.

Methods

Study Area

The study area consisted of the extent of Landsat 7 Path 24, Row 30 (42°29′49″ to 44°8′45″ N; 88°13′55″ to 90° 50′27″ W), which covered the majority of southern Wisconsin, USA (Fig. 1). The small proportion of this tile that covered Illinois and Iowa was not included in the analysis. The total area was approximately 29,750 km^2.

We adapted reed canarygrass dominance classes generated by Bernthal and Willis (2004) for use as a response variable, with potential predictor variables taken from the Wisconsin Initiative for Statewide Cooperation on Landscape Analysis and Data (WISCLAND) land cover database. Bernthal and Willis (2004) used Landsat 7 ETM+ imagery to map wetlands dominated by reed canarygrass in southern Wisconsin. Their methods classified only wetlands in the Wisconsin Wetlands Inventory (Wisconsin Department of Natural Resources 1984–1996). Bernthal and Willis (2004) identified three reed canarygrass pixel dominance classes: dominant: 80 to 100% reed canarygrass cover; co-dominant: 50 to 79% reed canarygrass cover; not dominant: 0 to 49% reed canarygrass cover. The accuracy of their mapping was field verified at 249 points. The accuracy of the *dominant, co-dominant,* and *not dominant* classes was 86, 41, and 69% respectively. This classification scheme was reduced to two categories for our analysis (dominant: 50 to 100% and not

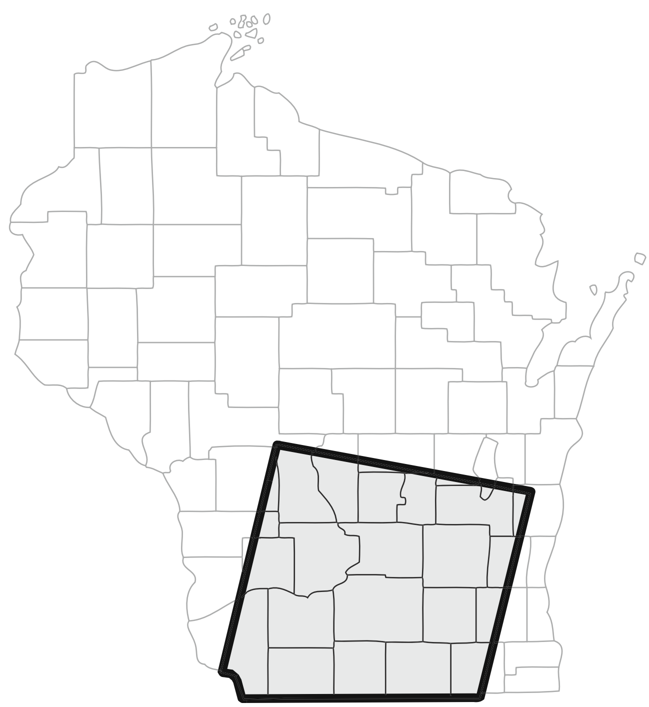

Fig. 1 The extent of the Landsat 7 image used by Bernthal and Willis (2004) to map reed canarygrass dominance in southern Wisconsin wetlands

dominant 0 to 49%) because of the low accuracy of distinguishing between *dominant* and *co-dominant* in the classification scheme of Bernthal and Willis (2004). This reduction improved overall accuracy to 82% (92% accuracy for the *dominant* class and 69% accuracy for *not dominant*).

We used the WISCLAND land cover database to generate land cover data that could be correlated to reed canarygrass abundance. The WISCLAND land cover data was developed using dual-date Landsat TM imagery with a final pixel resolution of 3,600 m^2 (60 m on a side). The accuracy of the WISCLAND land cover data is 89% at the level of classification used. The seven land cover types included in the analysis were wetland, agriculture, grassland, urban, forest, shrubland, and open water.

Both the reed canarygrass mapping and Wisconsin land cover were delineated into watersheds defined by the Wisconsin Department of Natural Resources watershed delineation maps using ArcGIS 9.1® (ESRI Corporation, Redlands, CA). These watersheds were delineated using USGS 7.5-min (1:24,000-scale) maps by interpreting topographic and hydrologic information. Watersheds were used in this analysis because the number of wetland patches was high (greater than 100,000 patches), and the eutrophication and sedimentation that enters wetlands and waterways impacts not only adjacent wetlands, but also wetlands downstream (Carpenter et al. 1998). The watershed unit used in this analysis yielded 96 watersheds with a portion of their wetlands classified for reed canarygrass dominance. Of these 96 watersheds; 19 were removed from the analysis because the Landsat image did not fully map the watershed, leaving 77 for analysis. The proportion of land cover types and the adjacencies of the wetlands within each watershed were analyzed using Fragstats 3.3 (McGarigal et al. 2002). The percent of wetlands dominated by reed canarygrass in each watershed was standardized by dividing the amount of area classified as *dominated* from the total classified wetland area of a watershed. Adjacencies were standardized by dividing the total number of adjacent edges of a particular land cover class by the total number of wetland edges in a watershed.

Data Analysis

Predictive models were developed using a regression tree analysis in the S-PLUS 8.0 statistical package (TIBCO, Palo Alto, CA) using the RPART version 3 module (Mayo Foundation 2002) from our pool of candidate variables (Table 1). This method repeatedly partitions the data defined by the predictor variables into zones that minimize the deviance of the response variable (De'ath and Fabricius 2000). Regression trees are useful for identifying interactions, making predictions of new cases on their own, as well as informing traditional model selection techniques (Vayssieres et al. 2000), and have been widely used to predict the distribution of plants and animals using ecosystem variables (Franklin 1998; Bourg et al. 2005; Usio et al. 2006). The trees were pruned so that each node had at least five observations and each leaf had at least two observations. The most parsimonious tree was chosen using the 1-SE rule where the best tree is taken as the smallest tree whose estimated error rate is within one standard error of the tree that minimizes deviance (Breiman et al. 1984).

Spatial autocorrelation of the response variable and predictor variables were evaluated to investigate whether reed canarygrass abundance predictions were influenced by any phenomenon at a spatial scale larger than the watershed scale used. A univariate Moran's I test was performed using the Geoda 0.9.5 software to analyze the spatial autocorrelation of each variable (Anselin et al. 2006). Pseudosignficance was calculated using 999 random permutations to calculate a reference distribution from which the Moran's I value could be compared. This spatial autocorrelation was accounted for in the candidate pool list of variables in the form of nearest neighbor averages (from one to 10 neighbor averages) of each watershed for each land cover candidate using GeoDa 0.9.5 (Anselin et al. 2006). These additional variables were included to determine if land cover at a spatial scale larger than the watersheds used in the analysis was helpful in predicting the percent of wetlands dominated.

Results

The average size of the watersheds was 434 km^2. Of the 77 watersheds used in the analysis, the average *percent of wetlands dominated by reed canarygrass* in classified wetlands was 17.4% (range 0.1 to 56.9%). The land cover that made up the largest proportion of the watersheds was the *proportion of agriculture*, with an average cover of 52.9% (range 9.4 to 81.3%). The land cover with the highest average adjacency to wetlands was the *adjacency to agriculture* with an average of 46.7% (range 3.9 to 84.4%). The second highest land cover in both categories was the *proportion* and *adjacency of forest*, which averaged 19.5 and 26.3% respectively.

The percent of wetlands dominated by reed canarygrass in watersheds was positively spatially autocorrelated. All but two of the predictor variables were also spatially autocorrelated, each with a similar pattern to that of the *percent of wetlands dominated by reed canarygrass* (Table 2). However, none of the nearest neighbor land cover averages were found to be significant predictors of the percent of wetlands dominated in the regression tree model, indicating that there were no significant land cover

Table 1 Candidate variables included in the regression tree model selection process. Adjacency refers to the adjacency of a land cover to the wetlands in a watershed. Proportion is the proportion of the watershed in each land cover class. Nearest neighbor watershed is the specified value of the watershed whose center is closest to the center of the primary watershed. Nearest neighbor averages were calculated by identifying the two nearest watersheds and averaging the specified value between those two watersheds. These values were also included for the nearest three, four, five, six, seven, eight, nine, and ten nearest neighbor watersheds

Adjacency	Proportion	Nearest neighbor watershed	Two through ten nearest neighbor watershed averages
Agriculture	Agriculture	Adjacency Agriculture	Adjacency Agriculture
Urban	Urban	Adjacency Urban	Adjacency Urban
Forest	Forest	Adjacency Forest	Adjacency Forest
Grassland	Grassland	Adjacency Grassland	Adjacency Grassland
Open Water	Open Water	Adjacency Open Water	Adjacency Open Water
Shrubland	Shrubland	Adjacency Shrubland	Adjacency Shrubland
		Proportion Agriculture	Proportion Agriculture
		Proportion Urban	Proportion Urban
		Proportion Forest	Proportion Forest
		Proportion Grassland	Proportion Grassland
		Proportion Open Water	Proportion Open Water
		Proportion Shrubland	Proportion Shrubland
		Proportion Wetland	Proportion Wetland

interactions occurring at a spatial scale larger than the watersheds used in our analysis.

Adjacency to agriculture to wetlands in a watershed best split the percent of wetlands dominated, followed by a secondary split using *adjacency to water*, with the final tree explaining 58% of the total variability in the data (Fig. 2). The second and third best initial partitions of the data used *proportion of agriculture* and *proportion of water*, each explaining 37% of the variability in the data. The *percent of wetlands dominated* was low, 11.2% on average, in watersheds with less than 43.8% of the wetland edges *adjacent to agriculture* (Fig. 2). The *percent of wetlands dominated* was two to three times higher at sites with greater than 43.8% of wetland edges *adjacent to agriculture*, but was further split into two groups. When *adjacency to agriculture* was greater than 43.8% and *adjacency to water* was less than 2.2%, *the percent of wetlands dominated* was highest (28.8%). When *adjacency to water* was greater than 2.2%, *the percent of wetlands dominated* averaged 21.6% (Fig. 3).

Discussion

Reed Canarygrass Invasion as a Function of Landscape Configuration

Experimental studies have shown that reed canarygrass is capable of outcompeting other vegetation when there are high nutrient levels, irregular hydrology, and high levels of sedimentation (Maurer and Zedler 2002; Werner and Zedler 2002; Maurer et al. 2003). All three of these types of disturbance are associated with agriculture (Skaggs and Breve 1994). It is not surprising, therefore, that watersheds with more agriculture have more wetlands dominated by reed canarygrass (Bernthal and Willis 2004). However, we found that the configuration of the landscape, which includes additional information over the composition of the landscape, is a better predictor of reed canarygrass abundance than composition. On the other hand, the regression tree excluded both *proportion of urban* cover and *adjacency to urban* land cover. Although urban land cover is associated

Table 2 Univariate Moran's I test results for spatial autocorrelation of predictor and response variables

Variable	Moran's I	Z Score	p
RCG Dominance	0.41	4.19	0.001
Adjacency Agriculture	0.51	4.85	0.001
Adjacency Urban	0.09	1.06	0.104
Adjacency Forest	0.67	6.68	0.001
Adjacency Grassland	0.31	2.91	0.003
Adjacency Open Water	0.26	2.55	0.100
Adjacency Shrubland	0.52	4.97	0.001
Proportion Agriculture	0.52	5.07	0.001
Proportion Urban	0.24	2.71	0.024
Proportion Forest	0.78	7.55	0.001
Proportion Grassland	0.33	3.17	0.003
Proportion Open Water	0.11	1.16	0.126
Proportion Shrubland	0.42	4.31	0.002
Proportion Wetland	0.22	2.50	0.022

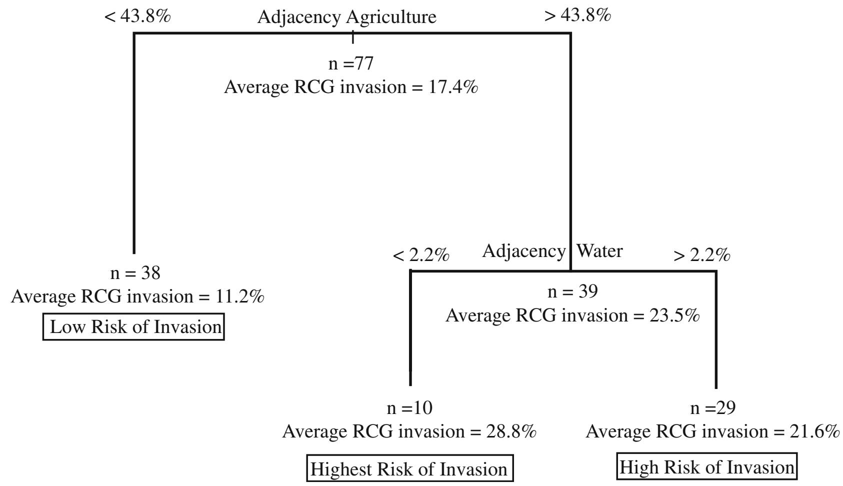

Fig. 2 Regression tree predicting the proportion of wetlands in a watershed dominated by reed canarygrass (RCG invasion) and the ranking of future invasion risk (R^2=0.58)

with eutrophication and sedimentation of wetlands (Wickham et al. 2002), the average *proportion of urban* land cover and *adjacency to urban* land cover within each watershed was low (1.4 and 2.3%, respectively). On a smaller scale, urban land cover maybe an important predictor of invasion, but it was not an important predictor at the watershed scale in this study, likely because it was a relatively rare land cover class.

The use of the regression tree model identified and informed an interaction between *adjacency to agriculture* and *adjacency to water* that likely would have been overlooked using traditional stepwise regression techniques because of the difficulty in evaluating every possible interaction between predictors. In watersheds with high levels of agriculture adjacent to wetlands, watersheds with a higher proportion of wetland edges adjacent to water have a lower percent of wetlands dominated. In these watersheds, it is possible that nutrients and sediment flow into wetlands from adjacent agriculture during storm events, but that the adjacency of water allows some of those nutrients and sediment to flow out of the wetlands to a location further downstream (Pimentel et al. 1995). In contrast, in watersheds with high adjacency to agriculture, but low adjacency to water, nutrients and sediment that flow into wetlands maybe less likely to flow out of the wetland. An alternative explanation is that wetlands with a higher adjacency to open water have a deeper water depth, which tends to reduce reed canarygrass dominance (Rice and Pinkerton 1993; Miller and Zedler 2003).

Interestingly, our analysis does not identify dispersal of reed canarygrass from intentionally planted pastures as important in predicting invasion. Pastures intentionally planted with reed canarygrass were classified as *grassland* in the WISCLAND land cover database, although they made up only a small part of this cover class. Therefore, dispersal of reed canarygrass propagules from pastures is not one of the direct influences of the agricultural land cover class on wetlands in this study. While dispersal from pastures to wetlands maybe an important component of invasion that was not captured by our analysis (Reinhardt Adams and Galatowitsch 2005), neither *adjacency to*

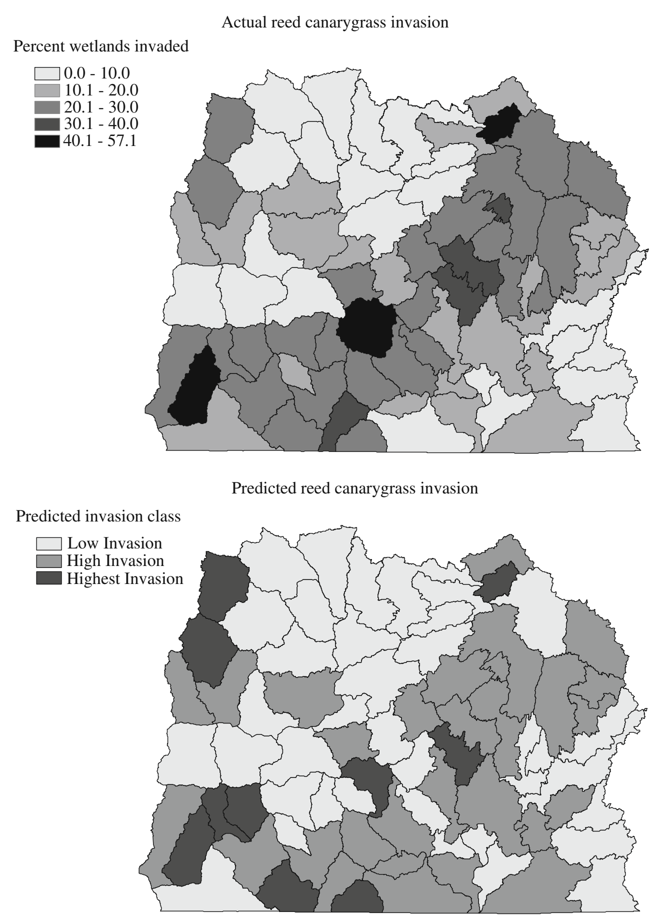

Fig. 3 The mapping of the percentage of wetlands in each watershed dominated by reed canarygrass contrasted against the predicted invasion class from the regression tree model. Note the spatial autocorrelation of reed canarygrass dominance

grassland, nor *proportion of grassland* were identified as significant predictors.

The expansion and intensification of agriculture following World War II degraded many thousands of acres of wetlands throughout North America (Pimentel et al. 1995). Our results support the hypothesis that this expansion of wetlands with high nutrient levels and frequent sedimentation events, the preferred environment of reed canarygrass, has allowed the species to expand its range greatly. While changes in the aggressiveness of reed canarygrass due to the introduction of foreign and bred populations may have also played a role in the expansion of this species (Lavergne and Molofsky 2004), human induced changes to the environment may have been one of the primary reasons for the invasion of reed canarygrass into wetlands.

Implications for Management

The primary methods of restoration for wetlands invaded by reed canarygrass are burning, physical removal, or repeated herbicide treatment followed by the replanting of desirable wetland species (Reinhardt Adams and Galatowitsch 2006). These types of restoration approaches do not directly address the changes to the environmental conditions that have occurred in wetlands and promoted colonization by reed canary grass. These approaches make the assumption that the environmental conditions that allowed the historical, diverse wetland plant communities to develop still exist, and that the only change leading to reed canarygrass invasion was the addition of their propagules to wetlands. In cases where the invasive has spread because of habitat change, however, the original environmental conditions that allowed native species to be successful in an area prior to invasion no longer exist (Davis et al. 2000), hence simply replacing invasives with natives is not likely to be a successful restoration strategy in the long-term.

When developing a management plan for a wetland invaded by reed canarygrass, the environmental changes and landscape context of a site must be accounted for. The landscape context of a site is good predictor of the current dominance of reed canary grass, and maybe an important predictor of both the prospects for management success and future invasion risk. The goal of restoration management should expand beyond the removal of the invasive species from a site to the goal of restoring wetlands to a resilient state in which they are either capable of resisting future invasion or able to enhance the ecosystem services provided by a site (Hobbs et al. 2006). In order to do this, we must manage the entire landscape, not just the wetlands themselves (Lindenmayer et al. 2008). The difficulty with this type of management is that restoration on a landscape scale is far more difficult than restoration of a local site. Restoration on a landscape scale requires working across public and private lands, convincing private landowners to add buffer strips around their wetlands and waterways and reduce fertilizer use, and the patience to evaluate the success of a restoration over a period of decades. For these reasons, it is not surprising that current management strategies focus on the direct removal of reed canarygrass.

Experimental studies that manipulate nutrient and sediment inputs in invaded wetlands over decades are necessary to determine whether controlling the nutrient and sediment inputs into a wetland is an effective method of reducing reed canarygrass dominance. A mesocosm study has shown that wet meadow vegetation was capable of outcompeting reed canarygrass under low nitrogen conditions (Perry et al. 2004). Long-term experiments with this type of restoration are necessary to evaluate its potential for widespread use.

Conclusion

Previous studies identifying factors that contribute to reed canarygrass invasion at the mesocosm scale—eutrophication, sedimentation, and hydrology—are supported by our landscape analysis. Our results additionally emphasize the importance of managing the landscape surrounding a wetland when attempting to restore wetlands invaded by reed canarygrass. Many restoration projects take place at the site scale, not because practitioners are oblivious to the effects of the surrounding landscape, but because the costs and political constraints deter attempts to conduct restoration at the landscape scale. However, if the goal of restoration is to restore the historic community and function of invaded wetlands, we argue that management of the entire landscape is essential. In sites where this is not feasible, a more constrained set of restoration goals that focus less on restoring community composition and instead explicitly on improving ecosystem function maybe more appropriate.

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